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Snow cover properties for skier triggering of avalanches

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Abstract

Snowpack characteristics for skier-triggered avalanches are described in order to better understand skier triggering, to improve snow profile observation and interpretation, to make suggestions for route selection and to provide a basis for further research. Our analysis is based on avalanche and snow profile data from skier-triggered avalanche sites in the Columbia Mountains of Canada and the Swiss Alps. Although these two mountain ranges have different climates, the characteristics for skier triggering are very similar. Whereas the snow cover in the profiles from the Columbia Mountains is more than twice as deep than in the ones from the Swiss Alps, the typical fracture depth (or slab thickness) is about the same (45 cm). Failure layer properties are very similar indicating favourable conditions for skier triggering and slab release. In both ranges, the failure layers are predominantly persistent, that is, they consist of crystals of surface hoar, facets and depth hoar, which are slow to metamorphose. The analysis has focussed on slab properties and weak layer properties, and in particular, their interaction. The findings support the simple model of skier loading in which skiers directly initiate failures in buried weak layers or interfaces.

Keywords: Avalanche forecasting; Avalanche formation; Avalanche mechanics; Skier triggering; Snow cover stability; Snow physical properties

1. Introduction

In most studies of avalanche accidents in Europe or North America (Schweizer and Lütschg, 2001; Logan and Atkins, 1996; Jamieson and Geldsetzer, 1996), approximately 85% of fatal avalanches are triggered by people. Yet, prior to Föhn's (1987a) critical stress model for human triggering, skier-triggered avalanches received little attention by researchers.

Earlier field studies of snow cover properties summarized the results of avalanches, most of which were released naturally or by explosives. Mellor (1968) has given a variety of snow conditions, based on earlier work, including weak layers, crusts, etc., overlain by a potential slab structure that could give rise to avalanches. Perla (1977) summarized the dimensions of slab avalanches, as well as some snowpack and terrain properties associated with avalanching. The article provided much-needed field data on slab avalanches, and is still widely referenced. In addition to similar measurements for 30

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avalanches, Stethem and Perla (1980) found a wide variety of crystals in failure layers and, in many cases, the crystals in failure layers differed little from those in adjacent layers.

Ferguson (1984) used cluster analysis and pattern recognition techniques to distinguish between stable and unstable snowpacks. She found wide variability in the snow cover characteristics within each group and had difficulty distinguishing between the groups, especially when no distinct weak layer could be found (interface failure). Since unstable data was more tightly clustered than stable data, it was possible to derive a reasonable model of unstable snowpack profiles. Close examination of clustering groups within the unstable data revealed that hard slabs, wet slabs and soft slabs each had three distinct layers: a slab, a shear zone, and a bed-layer. The slab was best characterized as unstable by load parameters (thickness, density, stress), whereas the weak layer was modelled primarily by texture parameters (grain type and size). Bed surface parameters describe the smoothness and consistency of the sliding layer (crusts, hardness, grain size, and thickness).

Föhn (1993) summarized the properties of about 300 weak layers underlying slabs, 20% of which was identified by avalanche investigations and the remainder by snowpack tests such as the rutschblock test (Föhn, 1987b). He found that 60% of failures occurred at weak interfaces and 40% in weak layers up to 60 mm thick. Eighty percent of the weak layers consisted of surface hoar, faceted crystals or depth hoar. He also reported the average and range of shear strength and stability indices for many weak layers and interfaces. Föhn et al. (1998) report the shear strength for 201 interfaces and 169 weak layers with a variety of grain types and Young's modulus for four layers of faceted crystals and four layers of surface hoar. Comparing two weak layers to adjacent layers, digital image analysis of plane sections revealed little difference in grain shape parameters and in grain size; however, the weak layers were slightly less dense.

Except for Jamieson and Johnston (1998), these previous studies have not focussed on skier-triggered avalanches. Except for Ferguson (1984) and, in a limited way, Föhn (1993), the previous studies have analyzed the weak layer in isolation from the properties of the slab and snow cover.

The present study comprehensively summarizes the properties of the snow cover, slab, weak layer or interface for almost 200 skier-triggered avalanches in Switzerland and Canada. These results are supplemented with a larger but less comprehensive data set of reported avalanches in both countries. The analysis of the snow cover and terrain properties is intended to provide insight into skier triggering of slab avalanches, and to assist with site selection for snowpack tests, profiles and explosive control, as well as snow profile interpretation and route selection. Further, the results should provide a basis for further research into skier triggering, especially on modelling.

2. Data sources

We explore four data sets of human triggered avalanches, two from Switzerland, and two from Canada (Table 1). For each country, we have a data set of reported avalanches with basic measurements (partly estimates) like width, slope angle, aspect, etc. These data sets are large: 635 cases for Switzerland from the winters 1987/1988 to 1996/1997 and 1136 cases for Canada from the winters 1989/1990 to 1999/2000. The other two data sets contain *investigated* human-triggered avalanches. In each case (95 for Switzerland, 91 for Canada), a snow profile was taken, usually 1 day after the release. These data sets will therefore be used to describe the snowpack conditions. As in any data set on avalanche measurements, there is a selection bias.

The Swiss data sets are based on avalanche reports of the Swiss Federal Institute for Snow and Avalanche Research (SLF). Avalanches are consis-

Table 1
Characteristics of data sets used

Type of data	Country of origin	Number of cases	Name of data set
Avalanche	Switzerland	635	S_REP
Avalanche/snowpack	Switzerland	95	S_INV
Avalanche	Canada	1136	C_REP
Avalanche/snowpack	Canada	91	C_INV

tently reported to the SLF if there is a serious involvement. Human-triggered avalanches that did not cause any damage are frequently not reported. Therefore, in 61% of the Swiss cases represented in the data set, a person was caught. Only the data from the region of Davos is quite complete including also many skier-controlled avalanches. The investigated cases for which a snow profile exists are often fatal accidents.

The Canadian data set is based on the avalanche reports of the two large helicopter skiing companies: Canadian Mountain Holidays (CMH) and Mike Wiegele Helicopter Skiing, both of which operate in the Columbia Mountains of western Canada. These operations report avalanches quite consistently, and in the very vast majority of the Canadian cases, the avalanches were intentionally triggered (skier-controlled) and nobody was caught or injured. The Canadian data might therefore be quite representative for the conditions for skier triggering but less representative of the avalanches in which people are caught or injured. This selection bias results in many more smaller avalanches in the Canadian than in the Swiss data sets.

3. Methods

Except as noted, snow cover properties are classified according to Colbeck et al. (1990). Measurement techniques are described in the *Observation Guidelines and Recording Standards for Weather, Snow and Avalanches* (CAA, 1995) but are similar in Switzerland and Canada.

For the analysis of the snow profiles, the hardness distribution within the snowpack (hand or ram hardness) was classified according to the profile types given in (Schweizer and Lütschg, 2001). The slab and the underlying snowpack have been characterized separately. Hand hardness for individual layers is indexed from 1 to 6 for Fist (F), Four-Finger (4F), One-Finger (1F), Pencil (P), Knife (K) and Ice (I), respectively. Intermediate values are allowed, e.g. 1–2, or 2 + . Geldsetzer and Jamieson (2001) treat this index as an exponent for a hardness measurement with units of stress.

Failure characteristics were given according to (Schweizer and Lütschg, 2001). When the failures occurred within or at the boundary of a thin (usually ≤ 3 cm) weak layer, the failure was characterized as weak layer failure—otherwise as interface failure, i.e. failure at a layer boundary (discontinuity).

To compare different data sets, we use two non-parametric tests. The Kruskal–Wallis (*H*-test) test for independent samples of different size, e.g. for comparing the fracture depth found in the Swiss and the Canadian sample; and the Wilcoxon signed rank test for related samples, e.g. if comparing layer characteristics case by case. For both tests, a p-value of significance can be given. If $p < 0.05$, the two samples are considered significantly different. Comparing categorical variables such as grain type or profile type, the distributions are compared by cross-tabulating the data and calculating the Pearson χ^2 statistic.

4. Comparing Swiss and Canadian data

In Section 4.1, we will first describe the results for the avalanche and terrain characteristics, relying mainly on the large data sets of reported avalanches, and then describe the snowpack conditions based on the two smaller data sets of investigated avalanches for which snow profiles are available (Tables 2–4). All tables are structured the same way: columns 2–5 and 6–9 present a key statistic (1st quartile, median, 3rd quartile) for the Swiss and Canadian data, respectively. The distributions of the Swiss and Canadian data are compared in Column 10 using the non-parametric Kruskal–Wallis test (*H*-test). In Columns 11 to 13, the key statistic is given for the combined data set. While combining samples of different distributions can be questioned, we do so to illustrate the variability of conditions under which skier triggering is possible. The results of combined samples must be interpreted with caution. However, even if the Swiss and Canadian samples are statistically significantly different in most cases, the results are nevertheless quite similar and comparable. Table 2 includes the avalanche, terrain and slab characteristics. The properties of the weak layer and the adjacent layers are described in Table 3. Table 4 summarizes the snowpack stratigraphy adjacent to an interface failure.

4.1. Type of avalanche

Only a few loose snow avalanches were reported. They contribute only 1–2% to the Swiss and 10% to the Canadian cases. Moist or wet snow avalanche are not frequent as well, and represent less than 1% in the Swiss and about 4% in the Canadian data set. Many of the moist/wet snow avalanches are loose snow avalanches. In the Swiss data set of reported avalanches, three of the four cases of wet snow avalanches are loose snow avalanches. In the Canadian avalanche data set, about 55% of the moist snow avalanches, and 87% of the wet snow avalanches are loose snow avalanches.

4.2. Dimensions of avalanche

The avalanches in the Swiss data sets are substantially larger than in the Canadian data sets due to the reporting and selection biases. The Canadian data sets include many small and shallow slabs of storm snow that have been intentionally triggered.

The median width in the Swiss reported avalanches is 50 m. The investigated avalanches are larger: median width is 70 m. In both Canadian data sets, the median width is 20 m (Table 2). Although avalanche width is related to the tensile strength of the slab (Jamieson and Johnston, 1992a), the difference in slab width between the Swiss and the Canadian avalanches is likely due to the selection bias mentioned previously rather than to generally stronger slabs in the Swiss Alps. The finding is however consistent with the fact that the Swiss investigated avalanches consist of more old snow slabs which tend to be stronger.

Most often, the length of the detached slab (between the crown and the stauchwall) is unknown, but the track length from the fracture line to the end of the deposit zone is estimated or occasionally measured. The median length of track is 150 m in the Swiss data set of reported avalanches, and 235 m in the Swiss data set of investigated cases. The avalanches in the Canadian data sets are substantially shorter. The median track length is only 50 m since very many small avalanches have been recorded.

The fracture depth is less influenced by the source of our data sets. The medians of the average fracture depths (measured vertically) from Canadian and Swiss reported avalanches are 30 and 50 cm, respectively (Table 2). Only about 2–3% of the average fracture depths are thicker than 1 m. Since the fracture depth is usually measured or estimated at the fracture line, it is frequently not representative of the triggering location (Jamieson and Johnston, 1998).

4.3. Terrain

The median slope angle is 38° for the Swiss reported avalanches and 39° for the Swiss investigated avalanches. Between the two Canadian data sets, there is a difference in median slope angle of 5°. Whereas the median slope angle in the investigated avalanches is 40°, it is only 35° in the reported avalanches (Table 2). The difference is likely due to the fact that slope angle is usually (under-)estimated in the reported avalanches, but measured in the investigated avalanches. The two Swiss data sets and the Canadian investigated avalanches have not significantly different slope angles ($p = 0.09$) (Fig. 1).

Northeast is by far the most frequent aspect in the two Swiss data sets. The distribution of aspects is very similar for the reported and investigated avalanches. The two Canadian data sets show differences between each other. Whereas the north is the most frequent aspect (42%) for the Canadian reported avalanches, it is the east (44%) for the investigated avalanches, probably because there are several easily accessed and often ski-tested east-facing slopes near two frequently visited Canadian study plots. All four data sets show skier triggering is more common on shady and/or lee slopes.

The elevation of human-triggered avalanches is typically 2400 m asl in the Swiss data sets and about 2000 m asl in Canada. This is above tree line in most parts of the Swiss Alps, and at around tree line in Canada. The lower median elevation in Canada might be due to the fact that tree skiing is quite popular with helicopter skiing.

4.4. Snowpack

In the following, we analyze the two data sets each with over 90 profiles from investigated avalanches. Our main interest is to explore the properties of the failure layer or interface in combination

Table 2
Swiss–Canadian comparison of human triggered avalanches
Except where noted results are for investigated cases.

Parameter	Swiss				Canadian				*H*-test	Combined		
	N	1st quartile	Median	3rd quartile	*N*	1st quartile	Median	3rd quartile	*p*	1st quartile	Median	3rd quartile
Width reported (m)	611	29	50	100	830	10	20	30	< 0.001	15	25	50
Width investigated (m)	94	35	70	120	85	8	20	30	< 0.001	16	35	89
Fracture depth reported (m)	522	0.3	0.45	0.6	1002	0.23	0.3	0.5	< 0.001	0.25	0.39	0.5
Fracture depth investigated (m)	95	0.4	0.5	0.7	91	0.27	0.4	0.55	< 0.001	0.35	0.46	0.6
Slope angle reported (°)	623	36	38	40	885	35	35	40	< 0.001			
Slope angle investigated (°)	95	38	39	40.5	91	36	40	43	0.50	37	39	42
Snow depth (m)	95	0.9	1.2	1.7	81	2.1	2.8	3.7	< 0.001			
RB score	60	3	3	4	46	2	3	4	0.67	2–3	3	4
Slab thickness (m)	95	0.36	0.52	0.67	91	0.28	0.41	0.6	0.034	0.3	0.46	0.63
Slab hardness	95	1–2	2	2	91	1+	2	3	0.23	1+	2	2–3
Slab temperature (°C)	83	−7.5	−4.5	−3.0	83	−8.0	−5.0	−3.5	0.25	−7.5	−5.0	−3.2
Slab density (kg m^{-3})	33	190	210	250	65	100	130	150	< 0.001	110	140	200

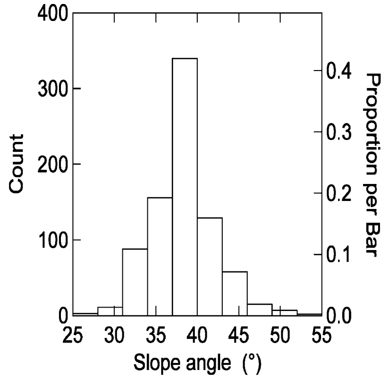

Fig. 1. Slope angle in starting zone of human triggered avalanches. Swiss-reported, investigated and Canadian-investigated cases are shown jointly ($N = 809$, 1st quartile: 37°, median: 39°, 3rd quartile: 41°).

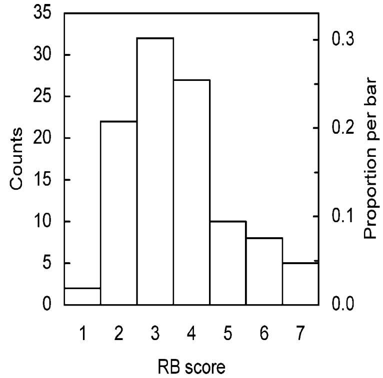

Fig. 2. Rutschblock scores of RB tests adjacent to human triggered slab avalanches. Swiss and Canadian cases shown together ($N = 106$).

with the adjacent layers. First, we describe some of the snowpack and failure characteristics in general.

Due to the distinct differences in climate, the median snow depth in the investigated cases in Switzerland was 1.2 m and in Canada more than twice as much: 2.8 m (Table 2).

In 35 out of the 95 Swiss investigated avalanches (37%), the slab consisted of storm snow, i.e. the failure was within the storm snow or between the storm snow and the old snowpack. In the Canadian data, the portion of storm snow avalanches is higher: 52%. For 45 out of the 91 Canadian cases, the age of the weak layer, i.e. the time since it was buried, was recorded. The median age is 11 days, the middle 50% ranged from 6 to 14 days, and the oldest weak layer was 56 days old when it was triggered by a skier. For the cases when the slab consisted of storm snow, the median age was 5 days, compared to 12.5 days for the 32 cases when the failure occurred in the old snow.

The failure was characterized as interface failure in 51% of the investigated Swiss cases, whereas the corresponding Canadian portion was 33%. In all other cases, there was a distinct thin weak layer found. For some of the weak layers, the failure could even be assigned to one of the layer boundaries. This would actually increase the interface failures, in fact to 58% in the case of the Swiss data set. Föhn (1993) reported about 60% of interface failures in his analysis of 300 snow profiles.

In most cases, a rutschblock test was performed. The median rutschblock score in both data sets is 3 (weighting) (Table 2). There is no significant difference between the two samples. Accordingly, the frequency distribution is given for the combined data sets (Fig. 2). In 76% of the cases, an RB score of 2, 3 or 4 was found.

4.5. Slab properties

The median slab thickness is 52 cm in the Swiss and 41 cm in the Canadian investigated cases (Table 2). The two samples are significantly different ($p = 0.03$) but with medians sufficiently close so that in Fig. 3 the slab thickness is shown for the combined data. As can be clearly seen in Fig. 3, in the majority

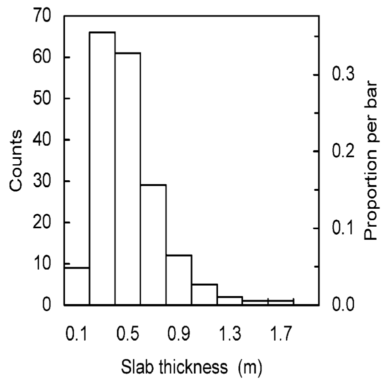

Fig. 3. Slab thickness of investigated avalanches. Swiss and Canadian cases shown jointly ($N = 186$).

of the cases (68%), the slab thickness is between 20 and 60 cm. The median slab thickness of the combined Swiss–Canadian data set is 46 cm; the mean and standard deviation is 50 and 26 cm, respectively. There is a significant difference in slab thickness for storm and old snow avalanches. The median thickness is 40 cm for the cases when the slab consisted of storm snow only, and 50 cm for the cases when the failure surface was within the old snow layers.

Since the portion of storm snow avalanches is different in the two data sets, the frequency of main grain type in the slab is not the same for the two data sets (Crosstab, Pearson χ^2, $p = 0.003$). Although the most frequently found grain type in the slab are the decomposing and fragmented precipitation particles in both data sets, the Swiss data set contains more small rounded grains, whereas the Canadian data set contains more precipitation particles (Fig. 4). Consistent with the higher proportion of old snow avalanches in the Swiss data, faceted crystals were found in some slab layers of the Swiss avalanches. The median average grain size of the slab in the Swiss data set is 0.75 mm.

Whereas the samples for average slab hardness and average slab temperature are not significantly different (H-test, $p \geq 0.23$), the density is significantly different (H-test, $p < 0.001$). The median slab density is 205 kg m^{-3} ($N = 33$) in the Swiss and 125 kg m^{-3} ($N = 65$) in the Canadian data set. The reason for the difference is not quite clear, but might be related to the higher portion of old snow slabs in the Swiss data (Table 2).

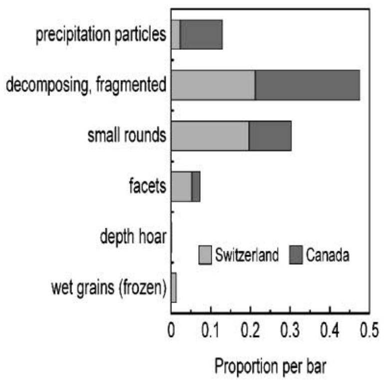

Fig. 4. Frequency of main grain type in slab for Swiss and Canadian avalanches (investigated cases).

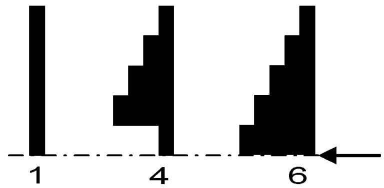

Fig. 5. Simplified slab structure (type of hardness profile) most frequently found in Swiss and Canadian data sets ($N = 186$). Frequency of profile types 1: 36%, 4: 7.5%, 6: 38%.

The median slab hardness index is 2 (4F) for both data sets. The most frequently found hardness index (mode) is 2 (4F) for the Swiss, and 1 (F) for the Canadian data set. The median of the average slab temperature is -4.5 °C for the Swiss, and -5.0 °C for the Canadian data set (Table 2). In both the Swiss and Canadian data sets, the profile types 1 (36%) and 6 (38%) are most frequently found (Fig. 5). Profile type 4 (7.5%) is the only other profile type that is found in more than 5% of the cases. All other seven types are in fact found, but only in a few cases (2–4%).

4.6. Weak layer

The median values of grain size, hardness, thickness and temperature of the weak layer for the Swiss and Canadian data are shown separately in Table 3, together with the properties of the two adjacent layers.

In the Swiss data, nearly exclusively (93%) weak layer grains with plane faces (persistent grain types) were found. The weak layers in the Canadian data frequently contain precipitation particles (30%) as well. The portion of surface hoar is very high (59%), higher than in the Swiss data set (37%). This might be due to either the generally more moist climate of the Columbia Mountains that favours surface hoar or/and the fact that the study of buried surface hoar layers was part of the Canadian research program (potential selection bias). The suggestion of a selection bias is supported by the fact that in a previous study on the fatal Canadian avalanche accidents by Jamieson and Johnston (1992b), the frequency of grain types in the failure plane was similar to the distribution of the Swiss data in this study. Statistically, the Swiss and the Canadian data sets are

Table 3
Swiss–Canadian comparison of properties of weak layer (WL), layer above (LA) and layer below (LB), and differences of properties

Parameter	Swiss				Canadian				H-test	Combined		
	N	1st quartile	Median	3rd quartile	N	1st quartile	Median	3rd quartile	p	1st quartile	Median	3rd quartile
WL grain size (mm)	47	1.5	2	2.5	61	1.75	3.5	6.5	0.003	1.5	2.5	5
WL hardness	47	1	1	1	54	1	2 −	2	0.002	1	1	2
WL thickness (cm)	47	1	1	2	61	0.5	1	1	0.023	0.5	1	1.75
WL temperature (°C)	42	−5.5	−3.6	−2.1	52	−6.6	−4.4	−3.4	0.014	−6.0	−4.0	−3.0
LA grain size (mm)	45	0.5	0.75	1.0	46	0.75	1	1.5	0.01	0.5	0.875	1.25
LA hardness	47	2	2–3	3	61	2 −	2 +	3	0.65	2 −	2 +	3
LB grain size (mm)	47	1	1.5	2	47	0.5	0.75	1.0	0.011	0.75	1.0	1.5
LB hardness	42	1	2	3–4	60	2	3	3 +	0.027	2 −	3	3 +
LA–WL grain size difference (mm)	45	0.75	1.25	1. 75	45	1.0	2.25	5.1	0.059	0. 75	1.5	3.25
LA–WL hardness difference	47	1	1	2	54	0	1	1 +	0.01	0–1	1	1–2
LB–WL grain size difference (mm)	47	0.0	0.5	1.0	46	1.0	3.25	5.75	< 0.001	0.25	1.0	4.25
LB–WL hardness difference	47	0	1	2–3	54	1 −	1	2 −	0.83	0 − 1	1	2

significantly different. Facets are more common in weak layers of Swiss investigated avalanches, and surface hoar in the Canadian investigated avalanches. Grain types with plane faces (surface hoar, facets, depth hoar) contribute 82% to all cases (Swiss and Canadian). Considering all types of failure, not only weak layer failures, but the interface failures as well, the portion of failure planes containing grains with plane faces is somewhat lower: 67% (Fig. 6). This is due to the higher portion of storm snow layers typical for interface failures. In the case of interface failures, the grain type of the softer of the two adjacent layers has been considered for the analysis.

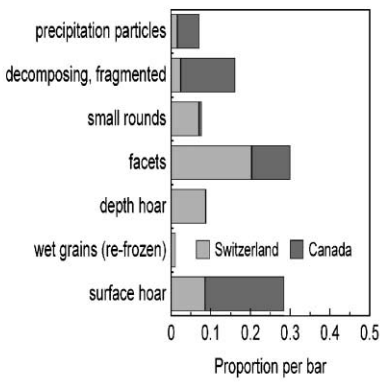

Fig. 6. Grain type in failure plane of investigated cases (Swiss and Canadian, $N = 186$). Weak layer and interface failures considered.

The size of the grains found in weak layers is a few millimetres smaller in the Swiss (median size: 2 mm), and larger in the Canadian data (median size: 3.5 mm) (Table 3). This is due to the high portion of surface hoar crystals found in the Canadian cases, the median size of which is 6 mm. The weak layers in the Canadian data set are harder (median: 2 −) than in the Swiss data set (median: 1). However, this difference may be due to a difference in measurement technique (McClung and Schaerer, 1993, p. 64). The median snow temperature in the weak layer is about −4 °C for both data sets. Yet, there are more cold temperatures found in the Canadian than in the Swiss data set, making the data sets significantly different ($p = 0.014$). Many of these very low temperatures are for shallow slabs. If the shallow slabs ($h \leq 20$ cm) would be omitted, the difference would no longer be conclusive (H-test: $p = 0.05$) (Fig. 7).

4.7. Snowpack layers above and below the weak layer

The characteristics of the layers above and below of the weak layer, as well as the weak layer are

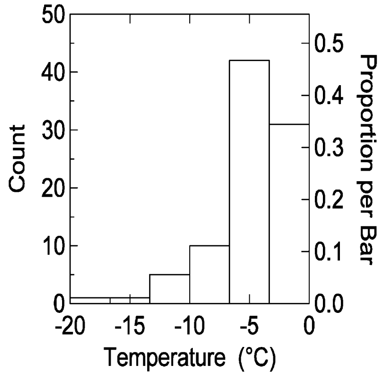

Fig. 7. Weak layer temperature. Swiss and Canadian investigated cases shown, except cases with shallow slabs (20 cm and less), $N = 85$.

summarized in Table 3. In the following, we will focus on differences of grain type, grain size and hardness between the Swiss and Canadian cases, respectively, for these layers.

In the layer above the weak layer, grain types associated with equilibrium metamorphism (precipitation particles, decomposed and fragmented particles and rounded grains) are most frequently found in the Swiss (62%) and the Canadian (86%) data. The higher portion in the Canadian data follows from the higher portion of storm snow avalanches. There is a significant difference ($p < 0.001$) in grain type between the layer above and the weak layer. The grain size in the layer above the weak layer is significantly smaller ($p < 0.001$) than in the weak layer, about 0.75 mm in the Swiss and about 1 mm in the Canadian data set (Fig. 8). The two data sets are significantly different ($p = 0.01$). The difference between the Swiss and the Canadian data set is likely due to the higher portion of fragmented and decomposing precipitation particles in the Canadian data. The hardness of the layer above the weak layer is significantly greater than in the weak layer ($p < 0.001$), about 2–3 in the Swiss and 2+ in the Canadian data set (Fig. 9). The median difference is one degree of hand hardness. There is no significant difference ($p = 0.65$) between the Swiss and Canadian data in the hardness of the layer above.

In the layer below the weak layer, again significantly different grain types are found compared to the weak layer ($p < 0.001$): about 70% facets, depth hoar and rounded facets in the Swiss, and only about 25% facets, but 73% fragmented and decomposing precipitation particles and small rounds in the Canadian data. The statistically significant difference ($p < 0.001$) between the Swiss and the Canadian data is a consequence of the different prevailing snow metamorphism in the Swiss and Canadian snowpack due to the different snow depth (1.2 vs. 2.8 m). The grain size in the layer below of the weak layer is significantly different ($p < 0.001$) from the weak layer, i.e. smaller (Fig. 8). The difference is very prominent for the Canadian, but not so large for the Swiss data set due to the higher portion of grains from kinetic growth metamorphism. The layer below of the weak layer is significantly harder than the weak layer ($p < 0.001$) (Fig. 9). The median difference is one degree of hand hardness index. There is statistically no difference between the Swiss and Canadian data

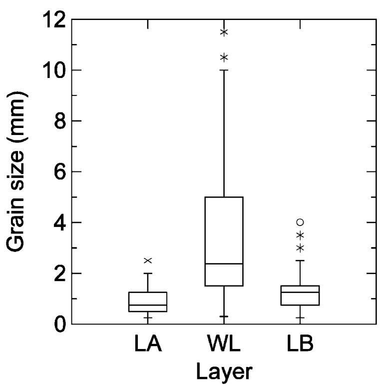

Fig. 8. Grain size in weak layer (WL), layer above (LA) and layer below (LB). Swiss and Canadian cases shown together.

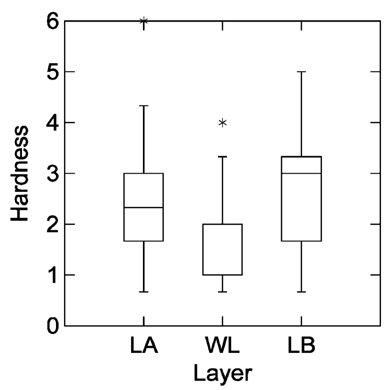

Fig. 9. Hand hardness index of weak layer (WL), layer above (LA) and layer below (LB). Swiss and Canadian cases shown together. Median weak layer hardness index is 1.

considering the hardness difference ($p = 0.83$), although the hardnesses of the layers below are significantly different ($p = 0.027$).

4.8. Layer above and below of an interface failure

As shown above, about 42% of all investigated cases were classified as interface failures. Therefore, in the following, we report on the difference between the layers between which the failure was observed.

The layer above the interface (Table 4) contains mainly small rounded grains of median size 0.6 mm in the Swiss and mainly fragmented and decomposing precipitation particles of 1.5 mm in size in the Canadian data. The median hardness of the layer above is 2 for both the Swiss and Canadian data, respectively. Comparing the Swiss and the Canadian cases, the grain type ($p < 0.001$) and the grain size ($p < 0.001$) are significantly different, but there is no significant difference in hardness (*H*-test, $p = 0.31$).

The layer below the failure interface (Table 4) contains mainly non-persistent grains for both the Swiss and the Canadian sample, but the samples are significantly different ($p < 0.001$). The high portion (48%) of crust-like layers in the Swiss data set is remarkable. The grains size is significantly different (*H*-test, $p = 0.004$), larger in the Swiss (median size: 1.5 mm), smaller (median size: 1 mm) in the Canadian cases. The hardness of the layer below as well is different for the two samples ($p = 0.039$): median hardness is 2–3 in the Swiss and 3–4 in the Canadian data.

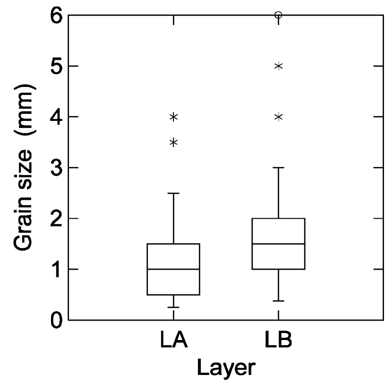

Fig. 10. Grain size in layer above (LA) and layer below (LB) of an interface. Swiss and Canadian cases shown together.

Comparing the two layers adjacent to the failure interface, the grain types are significantly different in the layer above and below ($p < 0.001$) for both samples. The grain size is significantly different between the layer above and below only in the case of the Swiss data ($p < 0.001$), but not for the Canadian sample ($p = 0.39$) (Table 4). However, also in the Canadian sample there is in general a significant difference in grain size. The median absolute difference is 0.5 mm ($N = 17$), smaller than in the Swiss cases ($N = 44$) for which the median difference in grain size is 1 mm (Fig. 10). The hardness of the layer above and below is not significantly different ($p = 0.39$) for the Swiss data, but is significantly different ($p = 0.002$) for the Canadian data. However, for both samples, there is a median absolute hardness difference of 1–2 and 2, respectively, for

Table 4
Swiss–Canadian comparison of properties (grain size and hardness) of layer above (LA) and layer below (LB) of interface failure, and differences of properties

Parameter	Swiss				Canadian				*H*-test	Combined		
	N	1st quartile	Median	3rd quartile	*N*	1st quartile	Median	3rd quartile	*p*	1st quartile	Median	3rd quartile
LA grain size (mm)	47	0.55	0.6	1.0	28	1.0	1.5	1.875	0.001	0.5	1.0	1.5
LA hardness	48	2 −	2	3	29	1 +	2	3	0.31	1–2	2	3
LB grain size (mm)	45	1.0	1.5	2.5	18	0.75	1.0	1.5	0.004	1	1.5	2.0
LB hardness	48	1	2–3	4	30	2	3–4	5	0.039	1	3	4
Absolute difference in grain size (mm)	44	0.5	1.0	1.5	17	0.25	0.5	0.75	0.012	0.25	0.75	1.25
Absolute difference in hardness	48	1	1–2	2–3	29	1	2	2 +	0.60	1	2	2 +

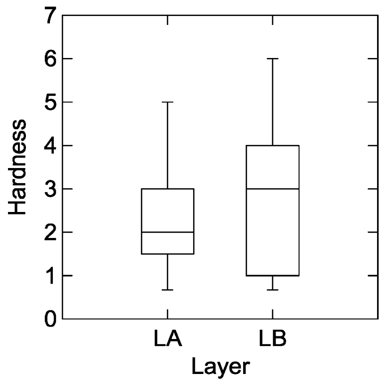

Fig. 11. Hand hardness index of layer above (LA) and layer below (LB) of an interface failure. Swiss and Canadian cases shown together.

the Swiss and the Canadian samples. The two samples of absolute hardness difference are not significantly different ($p = 0.60$) (Fig. 11). There are only three cases in the Swiss and one in the Canadian data with no hardness difference at all, representing about 5% of all cases ($N = 77$). The hardness difference can easily be shown more clearly if the data are pair-wise sorted so that always one of the two layers is the softer and the other the harder one (Fig. 12).

As shown above, there is frequently a prominent hardness difference between the layer above and the layer below. In the Swiss data set, the layer configuration "hard-over-soft" was nearly as frequently found as "soft-over-hard," 22 and 23 cases each,

Fig. 12. Hardness in layers adjacent to interface failure. Hardness difference is shown by pair-wise sorting the data. Swiss and Canadian cases are not significantly different and shown jointly ($N = 77$).

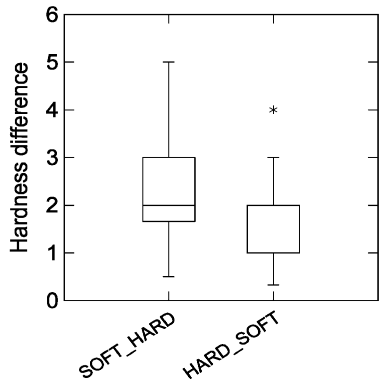

Fig. 13. Hardness difference between layer above and layer below an interface failure for the two cases when the upper layer is softer ("soft-over-hard," left) or the lower layer is softer ("hard-over-soft," right). The difference for the two layer configurations ("soft-over-hard," "hard-over-soft") is statistically significant (H-test, $p < 0.001$). Median hardness index difference is 1 for the "hard-over-soft" configuration. Swiss and Canadian cases are not different (H-test, $p = 0.70$) and shown jointly ($N = 73$).

respectively. In the Canadian sample ($N = 28$), the portion of "soft-over-hard" is higher (68%) than "hard-over-soft" perhaps due to the larger number of storm snow slabs intentionally triggered. In the case of the layer configuration "hard-over-soft," the hardness difference is statistically significantly ($p < 0.001$) smaller (median difference: 1, $N = 31$) than for the layer configuration "soft-over-hard" (median hardness difference: 2, $N = 42$) (Fig. 13).

It is obvious that the layers above and below the weak layer are not so different from the layers above and below a failure interface. For most parameters, there is no statistically significant difference. Only in the Canadian sample of investigated cases, the grain size in the layer above is significantly different (smaller in the layers above a weak layer) ($p = 0.017$), and the layers below are just about significantly harder (H-test, $p = 0.048$) below an interface failure than below a weak layer.

5. Summary and discussion

Although the present study of skier-triggered avalanches may be biased towards dry slabs, studies of avalanche accidents including avalanches that started without human triggers (e.g., Jamieson and Geldsetzer, 1996) indicate that only about 2% of fatal avalanches are loose and less than 15% are wet or moist, including wet or moist slabs.

The median slope angle for skier triggering is 39°, which is very close to the mean slope angles from other studies (e.g., Perla, 1977) that have not focussed on human-triggered avalanches.

Most skier-triggered avalanches in our Swiss and Canadian data are on north or east aspects, perhaps because these are most often shaded and/or lee slopes.

Most skier-triggered avalanches occur at or above tree-line perhaps because of skier preferences for this terrain and/or the effect of wind on slab formation.

The middle 50% of slab thicknesses from investigated avalanches range from 0.3 to 0.6 m (median 0.46 m). In 3.8% of cases, the slab thickness exceeded 1 m. However, less is known about the slab thickness at the trigger point. The fact that 82% of skier-triggered slabs were less than 0.7 m, supports the idea that in most, but not necessarily all cases of skier triggering, the skier is effective in initiating a failure in the weak layer/interface without the preexistence of a deficit zone (Schweizer, 1999; Schweizer and Camponovo, 2001). Where a weak layer and slab are present, skier triggering will be more likely where the slab is thinner and softer. Logan (1993) and Jamieson (1995) give examples of skier triggering where the slab is locally thin and/or weak.

As expected for slabs, which are by definition cohesive, most consist of layers of precipitation particles, decomposed and fragmented particles and/or rounded grains. However, in the thin snowpack area of the Swiss Alps, faceted crystals are also commonly found in slabs.

The middle 50% of slab temperatures (roughly in the middle of the slabs) range from -7.5 °C to -3.2 °C. Within this range, moderate changes in temperature can affect the stiffness of the slab (Schweizer, 1998) and consequently the stability for skiers (McClung and Schweizer, 1999).

In the most common profile of the slabs, hardness increased with depth. Soft conditions at the top prevailed. However, occasionally, other profiles such as wind slabs with a relatively hard near surface layer, were also skier-triggered.

The percentage of avalanches in which the slab included old snow ranged from 63% (Swiss) to 48% (Canadian) indicating the importance of observing and/or monitoring weak layers even after they are buried by a recent storm. This is further emphasised by considering the age of weak layers in the Canadian investigated avalanches (median age: 11 days).

The middle 50% of weak layer thickness ranges from 0.5 to 1.75 cm; however, many of the layers were only measured to the nearest centimetre and our definition of weak layers excludes most layers thicker than 3 cm. Nevertheless, it is clear that 1-cm-thick weak layers and weak interfaces can be important to operational forecasting programs, as well as snowpack evolution and forecasting models. Further, it is important to find such thin weak layers in manually observed snow profiles.

Combining the results for Swiss and Canadian investigated avalanches, 82% of weak layers was persistent. That is, they consist of faceted crystals, depth hoar or surface hoar. Such layers are also common in fatal avalanches (Jamieson and Johnston, 1992b). The shear strength of such layers is often lower than other layers of similar density (Jamieson and Johnston, 2001). Also, depth hoar and perhaps the other persistent forms exhibit brittle behaviour over a wider range of strain rates than rounded grains (Fukuzawa and Narita, 1993). Although sometimes it is difficult to identify in manual snow profiles, such layers are important to backcountry forecasting programs for recreationists.

The middle 50% of weak layer temperatures ranged from -6 °C to -3 °C. This is consistent with other studies not restricted to skier-triggered avalanches (e.g., Perla, 1977; Stethem and Perla, 1980). Within this temperature range, rapid changes in the material properties of weak layers are possible. Some of the challenges inherent to avalanche forecasting are probably related to predicting the behaviour of a material within a few degrees of its melting temperature.

The weak layers typically range from Fist to Four-Finger hardness. The layers above and below the weak layer are typically harder by one degree. For example, if the weak layer is Four-Finger (4F) hardness, the layers above and below are typically One-Finger (1F). Since the force for hand hardness tests is kept approximately constant and the area is varied by a factor of roughly 4 (Geldsetzer and Jamieson, 2001), the layers above and below are often several times harder, stronger and stiffer than the weak layer. This is an important clue to finding many weak layers in manual snow profiles. Such hardness differences are common in the snowpack and the presence of such a hardness difference does not, by itself, indicate instability. Also, the stress-and-strain concentrations associated with the stiffness difference between weak and adjacent layers are relevant to slab release models.

As reported by Stethem and Perla (1980) and Ferguson (1984) for avalanches with various triggers, a wide variety of grain types was found above and below weak layers and interfaces. However, persistent weak grain types such as facets and depth hoar are found more often in weak layers than in adjacent layers. Also, crusts are found more often in layers below than in layers above weak layers. In Swiss and Canadian investigated avalanches, 12% and 9%, respectively, involve a weak layer of facets overlying a crust.

The grains are significantly larger in the weak layer than in adjacent layers. In the Swiss avalanches, the grains in the weak layer are about 1.4 mm larger (about 11/2 times) than those in the layer above the weak layer and about 0.5 mm larger (about 1/3 times) than those in the layer below the weak layer. The difference in grain size between weak layers and adjacent layers is greater in the Canadian data probably because of the many weak layers comprised of large surface hoar crystals. Overall, weak layers have significantly larger grains than adjacent layers.

For interface failures, there is a median hardness difference of 1 or 2 degrees, again indicating a stress and strain concentration where the failure occurs. The layer of greater hardness can be above or below the weak interface. In the latter case, the hardness difference is even more prominent. There is as well a significant difference (0.75 mm) in grain size between the two layers adjacent to the failure interface. Such hardness or grain size differences are common in the snowpack and the presence of such differences does not, by itself, indicate instability. It is rather the combination of significant differences in grain type, grain size and hardness that tend to indicate instability.

The middle 50% of rutschblock scores near skier-triggered slab avalanches range from 2.5 to 4. While such scores are often associated with instability, higher scores do not conclusively indicate that skier triggering is unlikely since 12% of skier-triggered avalanches occurred on slopes for which the rutschblock score at a representative site was 6 or 7. Since snow stability varies spatially on avalanche slopes (Conway and Abrahamson, 1984, 1988; Föhn, 1987a,b, 1989; Jamieson, 1995, pp. 159–168) the stability at the trigger point was probably lower than at the rutschblock site. Based on rutschblock scores on slopes that were skier-triggered and on slopes that were skied but not triggered, Föhn (1987b), Jamieson (1995, pp. 169–173) and Jamieson and Johnston (1995) report the percentage of avalanche slopes that were skier-triggered for each rutschblock score. Although our data include some of the same results, they also found that at least 10% of skier-triggered slopes had rutschblock scores of 6 or 7. Clearly, a snowpack test that only involves an area of 3 m^2, which is often less than 1% of a start zone, cannot by itself reliably indicate instability. Other field observations including weather, snowpack and avalanche observations, must be considered to assess the probability of skier triggering for a particular slope.

6. Conclusions

We have conclusively characterized snowpack conditions found in skier-triggered avalanches. Many of these results are not surprising, but are consistent with the experience of many forecasters. However, conditions favourable for skier triggering, have never been documented and quantified comprehensively before.

The findings support the simple model of skier loading in which skiers directly initiate failures in buried weak layers or interfaces. The slab should preferably be soft to enable the skier to efficiently impart deformations to the weak layer. The slab has to be relatively shallow since the skier's impact strongly decreases with increasing depth. A distinct difference in hardness between the slab and the weak layer causes stress concentrations and favours fracture initiation. Accordingly, when travelling in the backcountry, areas of thinner-than-average snowpack may be potential trigger points, especially when a persistent weak layer exists in the snowpack. Therefore, areas of thinner-than-average snowpack are as well the preferred sites for snow profiles and to test snow stability.

While we have identified snow cover properties associated with many skier-triggered avalanches, these properties are not necessarily distinct from conditions in which skier triggering is rather unlikely. However, the results will assist with snow profile interpretation, site selection for stability tests, route selection, as well as models for skier triggering and snowpack evolution for avalanche forecasting.

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